Fluted Spiral Membrane Module for Reverse Osmosis of Liquids with Dissolved and Suspended Solids

Inventions and Innovations Program

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Final Report

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B. CONTENTS

SECTION 1: Introduction

SECTION 2: Narrative

A. Summary of the Original Project Goals

The overall goal of the project was to develop methodology for the fabrication of a fluted spiral module, produce a prototype module and test its performance. This goal was to be achieved in several stages as follows;

Formation of Fluted Membrane Leaf: A fluted membrane leaf will be pressed with a flute shaped horn against a complementary fluted anvil to form the flutes

Formation of Circular Membrane Leaf: A circular membrane leaf will be pressed with a circular horn against a complementary circular anvil.

Rolling of Fluted Membrane Module: Fluted membrane leaves and a circular membrane leaves will be glued to the permeate tube and rolled to form the module.

Testing of Module Integrity: The solute rejection and the permeate flux of the fabricated module will be evaluated for integrity.

Bench top Module Testing: The fluted membrane module will be used to concentrate simulated produced water and tomato juice on bench top scale.

B. Variance from the Project Goals

Formation of Fluted Membrane Leaf: A fluted membrane leaf was pressed successfully with a flute shaped horn against a complementary fluted anvil to form the flutes. The leaf retained the fluted shape after pressing as hypothesized.

Formation of Circular Membrane Leaf: A circular membrane leaf was pressed with a circular horn against a complementary circular anvil. The leaf retained the circular shape after pressing as hypothesized.

Rolling of Fluted Membrane Module: Fluted membrane leaves and a circular membrane leaves were attached to a perforated permeate tube and rolled to form the module.

Testing of Module Integrity: A protocol for integrity testing of fluted and circular individually was developed and used to test leaves before rolling modules. The solute rejection and the permeate flux of the leaves were evaluated for integrity.

Bench top Module Testing: The fluted membrane module was not subjected to any testing since the integrity of the fluted leaves was not acceptable.

C. Narrative Discussion of Project Results

Fluted Spiral Membrane Module

Reverse osmosis (RO) is the most economical method of removing salts from wastewater. Hardness of oil drilling produced water causes excessive fouling of RO membranes due to deposit formation. When feed water is seeded with nuclei of hardness causing compounds further deposits take place on the nuclei and not on the membrane and prevents fouling. This process called seeded reverse osmosis requires membrane modules that can accommodate high pressures required for reverse osmosis and suspended solids formed by growing seed material. Relatively inexpensive spiral modules cannot accommodate suspended solids. Only the tubular modules meet both these requirements. High cost of tubular membranes has prevented this process from becoming a commercial reality.

Development of a fluted spiral membrane module, which offers all the advantages of the tubular module at the cost of a spiral module, was the subject of this project. The fluted spiral module design completely eliminates the feed spacer of the conventional spiral module by employing a pair of membrane leaves where one leaf is formed in to flutes (corrugations) and the other leaf is semi-circular. When the pair of leaves is wrapped around the central permeate tube in the form of a spiral, the flutes form a multiplicity of channels. These channels serve as an unobstructed flow path for the feed thus eliminates the feed spacer grid (Figure 1).

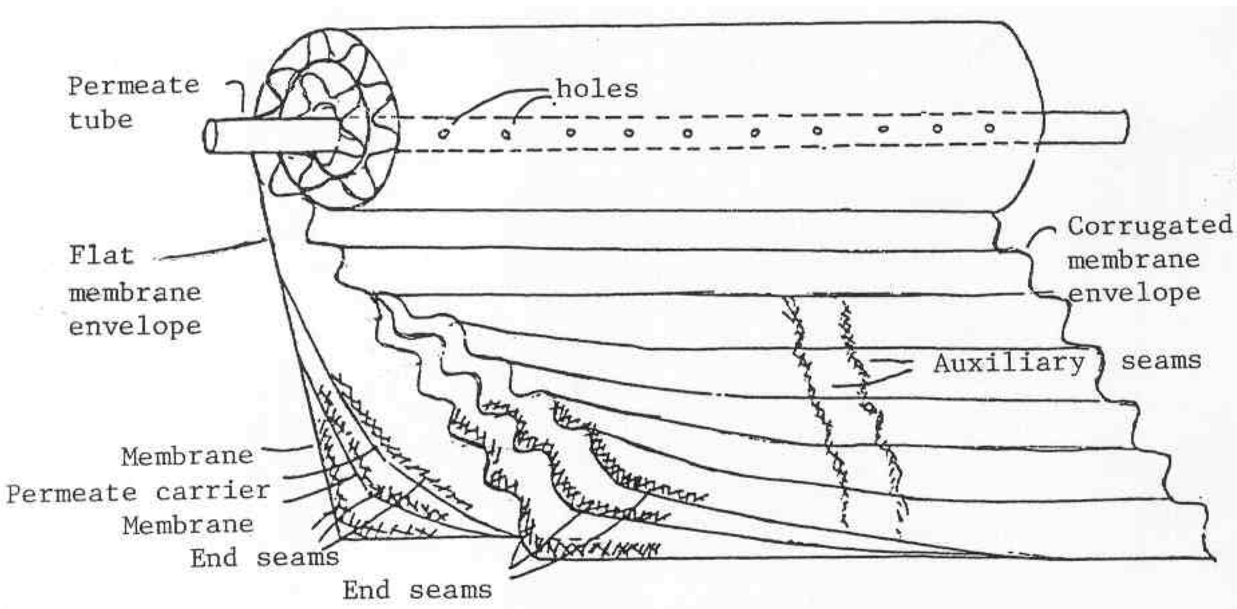

Figure 1. Fluted Spiral Membrane Module

This design completely does away with the feed spacer, which reduces the cost and weight of the module. It also eliminates obstructions in the flow path and reduces the parasitic drag due to feeder spacer grid. Nearly all the surface area that is in contact with the feed flow is active in filtration. Both sides of the membrane envelopes are subjected to the high pressure of the feed stream. These forces balance each other eliminating the need for external support unlike in the tubular membrane module. This is a unique approach with multiple advantages in comparison to previous approaches of introducing more and more expensive wide feed spacers.

This module has the potential to make seeded reverse osmosis a viable commercial process. Seeded reverse osmosis of the total produced water volume in US oil drilling industry will result in annual savings of over 1,250 Trillion BTU of energy compared to the use of triple effect evaporation. It will make heavy oil extraction more economical and also make a substantial new high quality water source available in arid regions.

Tomato juice pre-concentration, treatment of boiler blowdown, cooling tower blowdown, ground water remediation, landfill leachate treatment, feedlot runoff treatment and mining effluent treatment are some other reverse osmosis applications that would become economically feasible through the availability of this inexpensive membrane module.

Ultrasonic Welding Process for Membrane Leaf Formation

Ultrasonic welding is a relatively new process for joining plastic materials where high frequency (20 to 40 Hz) ultrasonic energy is transmitted through a tool called the horn to the plastic materials held between the two metal fixtures termed, horn and the anvil. The mechanical energy gets converted to heat and melts the plastics and fuses them together forming a strong seam. Formation of the fluted membrane leaf and the circular membrane leaf were accomplished by ultrasonic heating.

A Branson 910 ultrasonic welder and the power supply (Plate 1) were used in for with separate horn/anvil assemblies. Fabrication of horns and anvils, formation of membrane leaves and testing them for integrity were major activities of the project.

Plate 1. Ultrasonic Welder and Power Supply

Fluted Spiral Membrane Module Design Parameters

The spiral membrane module consists of several membrane leaves wrapped around a central permeate tube. It is theoretically possible to have a large number of short leaves or a small number of long leaves. A typical four-inch module consists of four leaves each approximately 40 inches long. A large number of shorter leaves were preferred for the fluted module to facilitate the fabrication procedure.

A computational model was developed to determine the parameters of the spiral module based on the mathematical equation of the spiral geometry. The spiral angle is limited to a maximum of about 270 to enable fabrication procedure. The model was used to calculate the number of leads and the length of the leaf for several possible angles (210, 240, and 270). The procedure was repeated for two possible thicknesses of membrane leaf pair (7/32, 1/4 and 9/32 inches). Table 1 is a listing the possible design parameters generated by this procedure.

Table 1. Spiral Membrane Module Parameters

Width of a Leaf Pair (inches)	Spiral Angle (deg)	Leaf Length (inches)	Number of Pairs of Leaves
7/32	210	4.0	9
7/32	240	4.5	8
7/32	270	5.1	7
1/4	210	4.0	8
1/4	240	4.5	7
1/4	270	5.1	6
9/32	210	4.0	7
9/32	240	4.5	6
9/32	270	5.1	5

The table indicates that a wide range of choices is available for the module design within the practical range. Eight pairs of leaves with 1/4 inch width per pair was selected for all the experiments in this work. This was convenient selection because it divides the circle into 8 angles of 22.5 degrees each.

Formation of the Fluted Membrane Leaf

Fabrication of a horn and anvil to form the fluted membrane leaf was the first major activity of the project. The critical requirement of the fabrication of the horn and anvil was that they mesh with extreme precision. The horn was fabricated using CNC (Computer Numerical Control) machining technology. Fabrication of anvil was done using EDM (Electrical Discharge Machining) technology. The first horn/anvil set failed to form satisfactory flutes. The failure was attributed to the use of too small radius of curvature (0.0625”). The second set, fabricated at a higher radius of curvature (0.125"). was successful in producing a membrane leaves with satisfactory flutes.

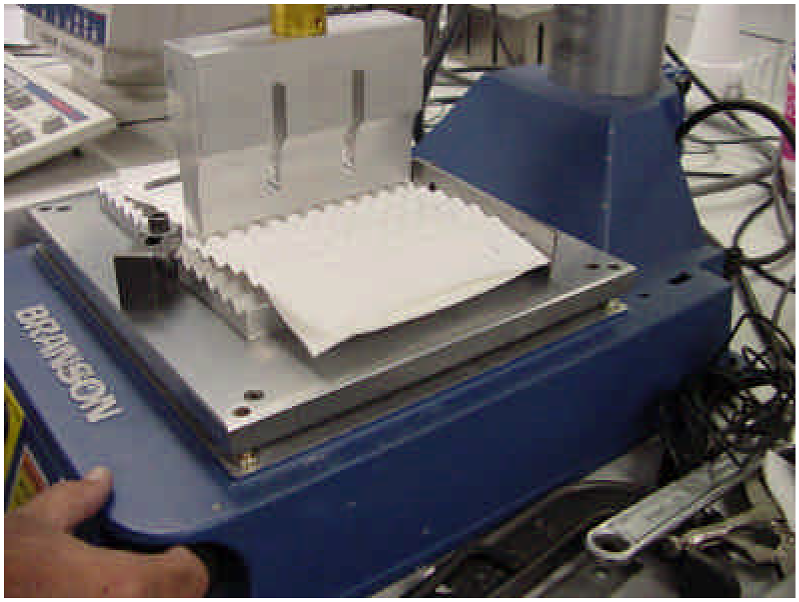

Plate 2. Formation of the Fluted Membrane Envelope by Welding Between the Horn and the Anvil

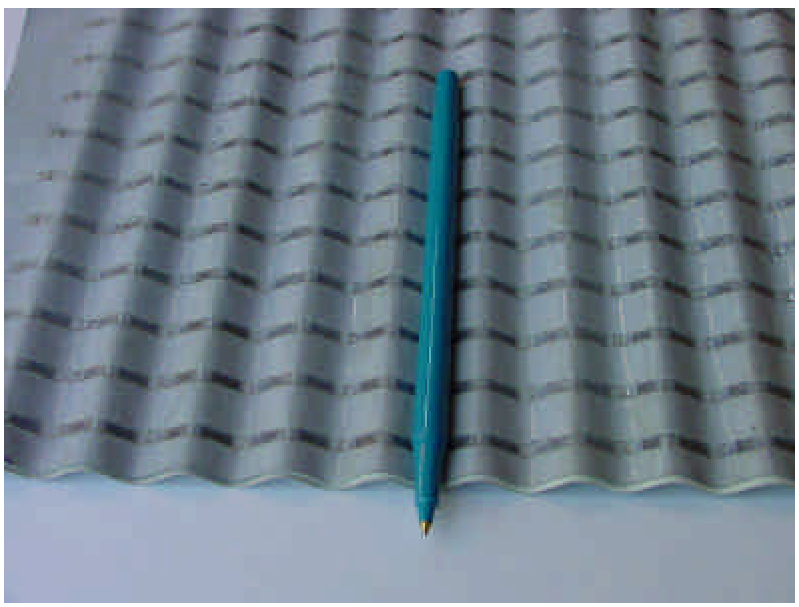

Plate 3. A Fluted Membrane Leaf Formed by the Ultrasonic Welding Process

The procedure for forming the fluted membrane leaf involved pressing the leaf pack between the horn and the anvil and then moving the leaf pack by one full wave and the repeating the step several times. The required length of 4.0" was obtained by pressing six waves. Plate 2 shows a fluted membrane leaf being formed using this horn/anvil set while Plate 3 shows a membrane leaf formed with this set.

Our hypothesis was that when the membrane leaf is ultrasonically welded at close intervals in the shape of flutes, the plastics would melt and solidify in the shape of flutes and will retain this shape permanently. The membrane leaves formed by the process retained the fluted shape permanently thus validating the hypothesis.

Formation of the Circular Membrane Leaf

The module design calculations (Table 1) indicated that the length of the leaf is about 4.0 inches. Forming this leaf in the spiral shape was found to be difficult. Therefore this leaf was shaped circular with radius equal to the average radius of curvature of the spiral shape. The radius thus determined was 1.25 inches. The leaf subtends an angle of 182º at the center of curvature. A horn with the 1.25 inches in radius of curvature, spanning 65º of the circle was designed for this purpose. Welding the 65º arc three steps while indexing the anvil completes a leaf with 182º arc. This allows for an overlap to ensure a continuous weld. Plate 4 shows this horn/anvil combination being used to form a leaf.

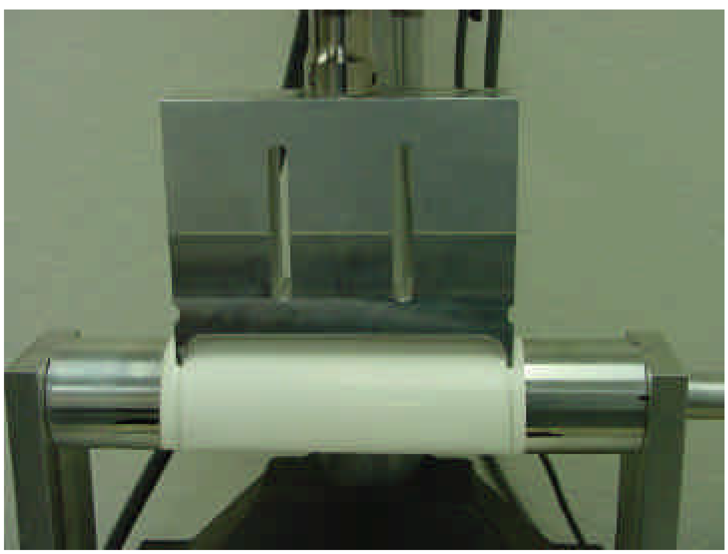

Plate 4. Formation of the Circular Membrane leaf by Ultrasonic Welding

Testing Integrity of the Membrane Leaves

The standard method of membrane module rolling does not allow for testing for integrity of individual membrane leaves. Integrity is tested after rolling the complete membrane module. It became apparent that in this project it is advantageous to test the integrity of welding of an individual leaf without rolling a module with multiple leaves. Therefore, a protocol was developed for testing of individual leaves. A 20 inch permeate tube was machined with a slot along the center. The membrane leaf was inserted in to the slot and sealed with polyurethane glue. Plate 5 shows a permeate tube and a membrane leaves prepared for integrity testing.

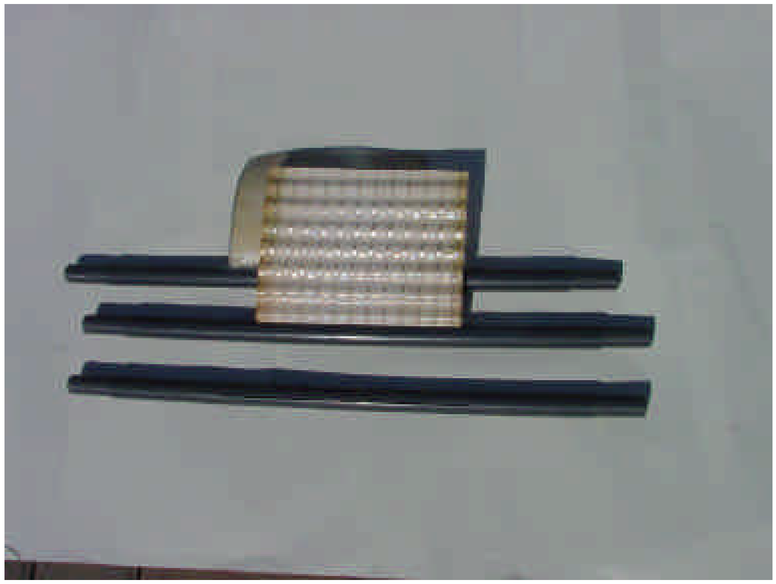

Plate 5. Membrane Leaves Prepared for Integrity Testing

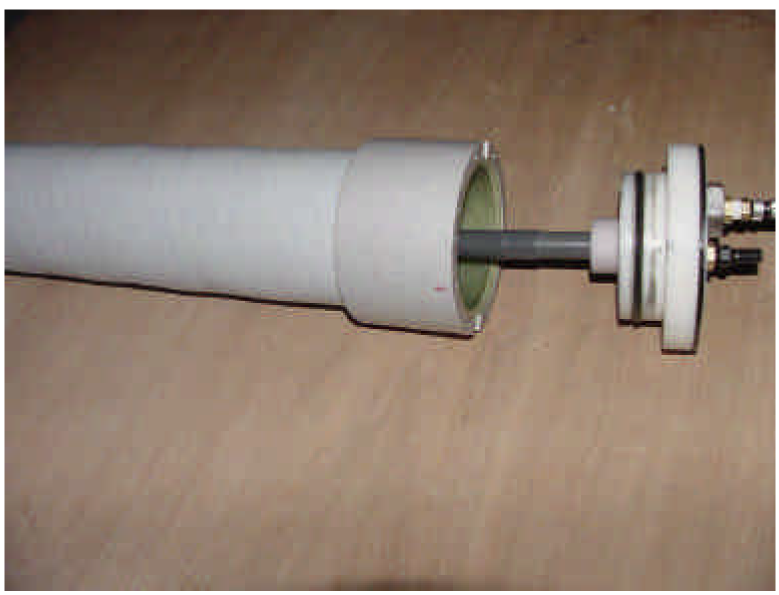

Plate 6. Membrane Housing used in Integrity Tests

The permeate tube with the membrane leaf was inserted into a membrane housing. (Plate 6) The housing was connected to a high-pressure pump. A testing solution containing 3% salt and 100 ppm methylene blue dye was pumped in to the housing at 400 psi. The permeate flux was recorded and the permeate was tested for salt and dye content. Acceptable integrity is indicated by over 95% rejection of salt and 100% rejection of dye. When these tests indicated loss of integrity, visual inspection of the seams show the traces of dye, which indicate possible paths of leakage.

The circular membrane leaves made initially showed some leakage at the seams formed at the edges of the horn. The horn and anvil were designed originally to fit exactly without the membrane leaf in between which did not allow for uniform sealing along the entire length of the seam. The anvil was modified to allow a uniform gap allowing for the thickness of the membrane leaf. This modification, improved the integrity of the seal of the circular leaf to acceptable range.

Once the acceptable horn/anvil configuration was found several setting of the ultrasonic welder were tested. The pressure of 60 psi and a weld time of 0.5 seconds were found to produce good seams. Higher pressures and longer weld times did not improve the quality of the seams.

The fluted membrane envelope made initially also showed some heavy leakage at the bends. This also was attributed to non-uniform gap between the horn and the anvil when the membrane envelope is held in between. The fluted horn was modified several times to allow for the thickness of the membrane leaves and hence to improve the uniformity of the seam. These modifications decreased the leakage dramatically. It was possible to produce several fluted membrane leaves with acceptable integrity with the improved horn/anvil setup. However, it was not possible to produce fluted membrane leaves with acceptable integrity consistently.

Rolling of Fluted Membrane Module

The selected fluted spiral module design contained 8 pairs of leaves each measuring 4.0 inches in length. Eight fluted leaves with about 5 inches of tail length were prepared first by the procedure detailed earlier. Plate 7 shows the stack of these leaves. One membrane and the permeate spacer from the tail of one fluted membrane leaf was laid together with one membrane from the next fluted membrane leaf and welded in the form of a circular membrane leaf. This procedure was repeated eight times to form a continuous membrane pack containing eight fluted leaves connected by eight circular leaves. Plate 8 shows the welding process while Plate 9 shows the continuous membrane pack formed by this process.

The next step was to attach the continuous membrane pack on to the permeate tube. A 20 inch CPVC permeate tube with perforations was used to assemble the module. The permeate tube was held by a matching collet on an indexing head. The membrane pack was inserted into the permeate tube and ultrasonically welded on to the permeate tube using a specially fabricated horn. In this case the permeate tube functioned as the anvil. This procedure was repeated eight times while indexing the permeate tube by 22 ½ degrees each time. The procedure was repeated at the opposite end. Polyurethane glue was applied to the gaps at the joint between the membrane pack and the permeate tube. Plate 10 shows a module after this stage. The membrane pack was rolled and inserted in to the sleeve to complete the process. Plate 11 shows the completed module in the sleeve.

Plate 7. Stack of Fluted Membrane Leaves

Plate 8. Connecting Eight Fluted leaves by Forming Circular Leaves

Plate 9. Continuous Membrane Pack Formed by Eight Fluted Leaves Interconnected through Eight Circular Leaves

Plate 10. Continuous Membrane Pack Affixed to the Permeate Tube

Plate 11. Membrane Pack Inserted into the Sleeve

Testing of the Fluted Spiral Membrane Module

The fluted membrane leaf did not possess sufficient integrity consistently to justify further testing. Therefore, membrane modules incorporating the fluted membrane leaves were not expected to possess sufficient integrity to make further testing meaningful. However, circular membrane leaves made with ultrasonically welded seams met the integrity requirements. Therefore, we decided to subject a single circular membrane leaf to a series of performance tests to confirm the hypothesis that ultrasonic welding produces acceptable seams.

The performance tests included pressure scans and a concentration scans. The pressure scan was conducted by changing pressure while maintaining all other system parameters constant. Concentration scan was conducted by changing the concentration while maintaining all other system parameters constant.

The pressure scan were conducted with a solution of 1% salt in tap water. The pressure was held at 200, 400, and 600 psi during the pressure scan. The flux characteristics observed during a pressure scan is shown in Figure 2. The permeate flux increased uniformly as the pressure increased. This was the expected behavior.

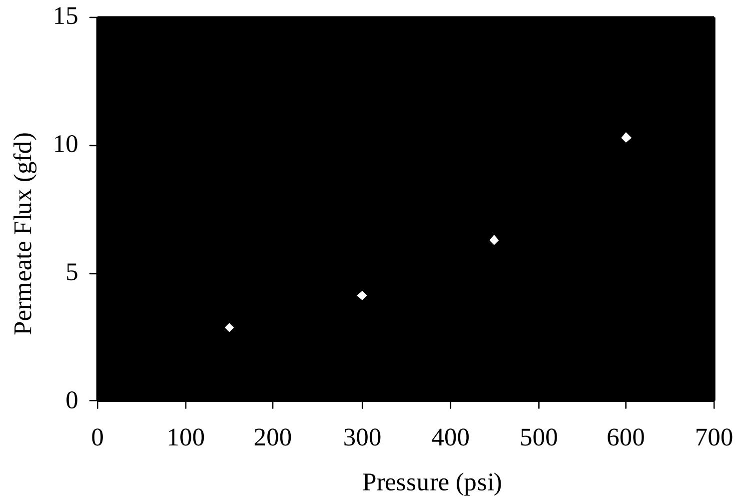

Figure 2. Flux Characteristics during a Pressure Scan - Temperature 75 F

Rejection of salt by the membrane is the critical criterion in evaluating the integrity of the membrane. The permeate and the retentate were sampled at each data point and the electrical conductivity of the samples were measured. Salt rejection by the membrane was evaluated by assuming that the electrical conductivity is proportional to the salt concentration. Table 2 lists the salt rejection characteristics observed during a pressure scan.

Table 2. Salt Rejection Characteristics during a Pressure Scan
Temperature 75 F

Pressure	Electrical Conductivity (mS/cm)		
(psi)	Retentate	Permeate	Rejection %
150	21.2	1.80	91.5
300	20.8	1.75	91.6
450	20.8	1.75	91.6
600	21.4	1.65	92.3

Increase in pressure increases water permeation rate more than the salt diffusion rate. Therefore, salt rejection is expected to improve with increase in pressure. This trend was not detected during the pressure scan. This was attributed to the limited number of data points also to possible leakage through imperfections.

A concentration scan was conducted with a salt solution to evaluate the flux and rejection characteristics under conditions encountered during concentration. The flux characteristics observed during the concentration scan are shown in Figure 3. The permeate flux decreased as concentration increased. This was due to increase in osmotic pressure which reduces the effective transmembrane pressure available for driving the permeate through the membrane.

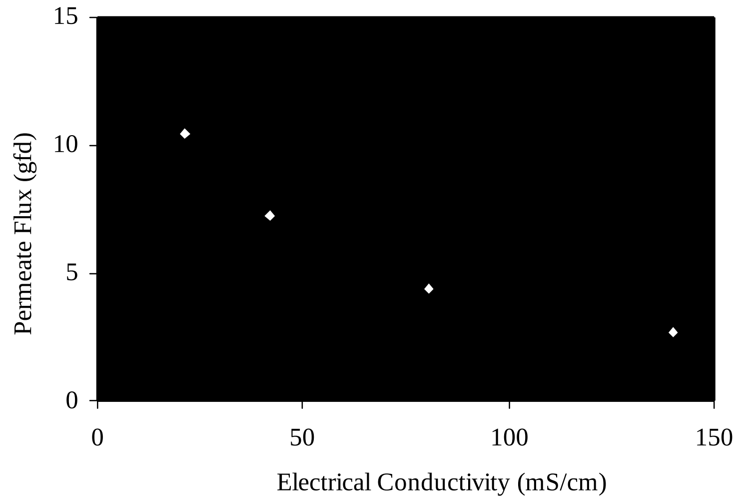

Figure 3. Flux Characteristics during a Concentration Scan

Table 3 lists the rejection characteristics observed during the concentration scan. Rejection decreased moderately with the increase in concentration. This is the expected behavior.

Table 3. Rejection Characteristics during a Concentration Scan
Pressure 400 psi – Temperature 75 F

Electrical Conductivity (? S/cm) Permeate	Retentate	Rejection (%)
21.4	1.72	92.0
42.0	4.60	89.0
80.6	9.83	87.8
140.0	17.80	87.3

The tests were successful in validating the integrity of the ultrasonically welded seam by demonstrating several important characteristics expected in membrane filtration.

1. The permeate flux increased with increase in pressure
2. Permeate flux decreased with increase in concentration
3. Rejection decreased with increase in concentration

Overall the electrical conductivity rejection of the circular membrane leaf was lower than the rejection shown by commercial membrane modules. This was attributed to minor damages to the sensitive membrane surface during the manual welding and assembling process. This situation should improve when the process is more automated with less human contact.

D. Completed Milestone Table – Attachment A

	Milestone	Original Planned Completion Date	Revised Planned Completion Date	Actual Completion Date	Responsible Organization	Original Projected Cost (Fed/Non-Fed)	Revised Projected Cost (Fed/Non-Fed)	Actual Competed Cost (Fed/Non-Fed)	Milestone Notes
1	Fluted Envelope	9/30/01	11/30/01	6/30/02	Scincep	15,000/ 8,000	15,000/ 4,000	15,000/ 4000	
2	Fluted Module	12/31/01	7/31/02	12/31/02	Scincep	10,000	10,000/ 4,000	10,000/ 4000	
3	Module Integrity	1/31/02	7/31/02	12/31/02	Scincep	5,000	5000		
4	Module Testing	2/28/02	1/30/03	4/15/03	Scincep	5,000	5,000		
5	Final Report	3/31/02	4/15/03	6/15/03	Scincep	5,000	1,655.44		

E. Final Gantt Chart – Attachment B

		Months from Award																							
Task	Title	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Obtain Supplies																								
2	Formation of Envelope				R	R	R	R	R	R	R	R	R												
3	Semi-Annual Reports						R																		
4	Rolling of Fluted Module													R	R	R									
5	Testing of Module Integrity																								
6	Bench-top Module Testing																			R	R				
7	Attend Annual Project Review	**TBD**																							
8	Data Analysis and Reporting																			R	R	R	R	R	R

R – Revised project schedule

E. Updated Energy, Waste, and Economic Savings

The installed unit for the *I&I project* technology is ______Separate 1 lb water_____.

The installed unit for the *comparable competing* technology as presented in the original proposal is __________separate 1 lb water

Energy Savings

Provide the energy savings for the project technology versus the comparable competing technology.

The *projected* energy consumption for the *project* unit in Btu/yr/unit was (at the beginning of the project) __________32 Btu/lb_______________.

The energy consumption for the *I&I project* unit in Btu/yr/unit is ____32 Btu/lb_________________.

Provide assumptions and references for the derivation of your values. *(Refer to Attachment H for energy conversion factors*)

The energy consumption for the *comparable competing* unit in Btu/yr/unit is _________318 Btu/lb__.

Provide assumptions and references for the derivation of your values. *(Refer to Attachment H for energy conversion factors*)

Environmental Savings

Provide the environmental savings for the project technology versus the comparable competing technology.

The *projected* wastes other than power generation emissions for the *project* technology in tons/yr/unit using the *I&I project* unit described above (at the beginning of the project) were:

Waste 1 ______________________________
Waste 2 ______________________________
Waste 3 ______________________________

Identify wastes other than power generation emissions for the *I&I project* technology in tons/yr/unit using the *project* unit described above:

Waste 1 ______________________________
Waste 2 ______________________________
Waste 3 ______________________________

Identify wastes other than power generation emissions for the *comparable competing* technology in tons/yr/unit using the *comparable competing* technology unit described above:

Waste 1 ______________________________
Waste 2 ______________________________
Waste 3 ______________________________

Provide assumptions to allow reviewers to understand the derivation of the stated values.

Economic Savings

Provide the economic savings for the project technology versus the comparable competing technology.

The *projected* unit cost for the *I&I project* technology (at the beginning of the project) was ________________________________

Define the unit cost for the *I&I project* technology ________________________________

Define the unit cost for the *comparable competing* technology _____________________

Provide assumptions to allow the reviewers to understand the derivation of the stated values.

F. Fuel /Energy Source Btu Conversion (Table) - Attachment D

Fuel Source	Btu/Barrel	Btu/Gallon	Btu/Pound	Btu/ft^3
Crude Oil	6 x 10^6	142 x 10^3	18.6 x 10^3	1 x 10^6
Fuel Oil – 6	6.2 x 10^6	150 x 10^3	17.8 x 10^3	1.1 x 10^6
Fuel Oil – 2	6 x 10^6	140 x 10^3	18.6 x 10^3	1 x 10^6
Gasoline	5.2 x 10^6	126 x 10^3	18.9 x 10^3	940 x 10^3
Propane – L	3.8 x 10^6	92 x 10^3	19.9 x 10^3	690 x 10^3
Wood	-------	-------	6.5 x 10^3	148 x 10^3
Natural Gas	87 x 10^6	2 x 10^3	21 x 10^3	1 x 10^3
Methane	87 x 10^6	2 x 10^3	21 x 10^3	1 x 10^3
Methanol	2.9 x 10^6	69 x 10^3	9.6 x 10^3	517 x 10^3
Ethane	-------	-------	20 x 10^3	1.8 x 10^3
Ethanol	3.7 x 10^6	87 x 10^3	12 x 10^3	652 x 10^3
Hydrogen	-------	-------	51 x 10^3	270
CO	-------	-------	4.3 x 10^3	316
Coal - Bit.	-------	-------	12.6 x 10^3	800 x 10^3
Coal - Lig.	-------	-------	8.6 x 10^3	541 x 10^3
Coal - Ant.	-------	-------	12.6 x 10^3	800 x 10^3
Carbon	-------	-------	14.6 x 10^3	1.9 x 10^6
Ethylene	-------	-------	20 x 10^3	1,477

Electrical Generation (32.4% efficient Power Plant) – 10,500 Btu/kWh

G. Final Cost Sharing – Attachment F

#	Company Name	Company Type*	In-Kind Contribution	Cash Contribution	Total
1	Scinsep Systems	Contractor	6,000.00		6,000.00
2	Dirk de Winter	Consultant	2,000.00		2,000.00
3					
4					
5					
	DOE				36,655.44
	Total				44,655.44

H. Partners and Contractors – Attachment G

#	Company Contact	Address	City	ST	Zip	Phone / Fax / e:mail
1	Dirk de Winter	401 Jones Road	Oceanside	California	92054	760-901-2537
2						
3						
4						
5						

List all companies involved in the project (equipment vendors, consultants, subcontractors, customers etc. and provide a brief narrative discussing the role of each partner.)